AD-A085 672   OHIO STATE UNIV RESEARCH FOUNDATION COLUMBUS   F/G 20/4

FLUID DYNAMICS OF MULTIPLE NOZZLE ARRAYS AND RADIAL FLOW DIFFUS--ETC(U)

APR 80   S L PETRIE, J D LEE   AFOSR-76-2956

UNCLASSIFIED   AFOSR-TR-80-0456   NL

1 OF 1
AD A
085672

END
DATE
FILMED
7-80
DTIC

I

(18) (19)

AFOSR TR- 80-0456

(12)

LEVEL II

FINAL REPORT
AFOSR 76-2956
OSURF 784336

(6)

# FLUID DYNAMICS OF MULTIPLE NOZZLE ARRAYS AND RADIAL FLOW DIFFUSERS

ADA085672


By

(10)

S. L. PETRIE

J. D. LEE

(12) 28

THE OHIO STATE UNIVERSITY

THE AERONAUTICAL AND ASTRONAUTICAL RESEARCH LABORATORY

DEPARTMENT OF AERONAUTICAL AND ASTRONAUTICAL ENGINEERING


(9)

FINAL REPORT, 1 Oct 77 - 31 Dec 79

To

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

On

(15)

GRANT AFOSR-76-2956

(16) 2307 (17) A2

(11)

80 6 11 025

Apr 1980



267360

JW

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER AFOSR-TR- 80-0456 | 2. GOVT ACCESSION NO. AD-A085 672 | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle) FLUID DYNAMICS OF MULTIPLE NOZZLE ARRAYS AND RADIAL FLOW DIFFUSERS | | 5. TYPE OF REPORT & PERIOD COVERED Final 10/1/77-12/31/79 |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s) S. L. Petrie and J. D. Lee | | 8. CONTRACT OR GRANT NUMBER(s) AFOSR 76-2956 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS The Ohio State University Research Foundation, 1314 Kinnear Road Columbus, Ohio 43212 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2307/A2 61102F |
| 11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Air Force Air Force Office of Scientific Research/NA Bolling Air Force Base, D.C. 20332 | | 12. REPORT DATE April, 1980 |
| | | 13. NUMBER OF PAGES 27 |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) | | 15. SECURITY CLASS. (of this report) Unclassified |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

TURBULENCE MODELING
LASER
DIFFUSERS
NOZZLE ARRAYS
EJECTORS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes the theoretical and experimental research conducted under AFOSR Grant 76-2956, dealing with the fluid dynamical interactions in free shear layers and diffuser-ejectors. The objectives of this research were (a) to provide characterization of the fluid dynamical mixing layers typical of those in supersonic transfer lasers and in mixing gas dynamic lasers, and (b) to examine the mixing and induction characteristics of ejectors capable of providing pressure ratios typical of those associated with radial flow laser diffusers.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE 267360 Unclassified

80 6 11 025

## LIST OF FIGURES

## INTRODUCTION

The characterization of the fluid dynamical aspects of mixing layers allows assessment of the relative influences of parameters such as turbulent scale and intensity, energy spectrum and density fluctuations on the mixing layer structure. A versatile experimental facility was assembled and experimental techniques were developed to measure the steady state and certain of the time resolved gasdynamic flow properties. Supporting theoretical analyses have also been conducted which allow variation of the turbulence model employed to characterize the mixing within the shear layer. These studies were concerned primarily with the fluid mechanical aspects of gas flow lasers, and did not involve considerations of the lasing process. However, certain of the experimental techniques which have been developed during the course of this research are being applied in laser facilities at the Air Force Weapons Laboratory (AFWL).

The analyses of diffusers and ejectors provides information on the deceleration of the low-pressure, supersonic flow in the laser cavity and its subsequent discharge to the atmosphere. With the viewpoint of operation in a minimal volume and with high overall efficiency, e.g. as on board an aircraft, it is necessary that each component of the device be as compact as possible, reliable and have a high response rate. Multiple channel diffusion appears to offer prospects of small size as well as efficiency while the ejector pump is attractive for its fast on/off characteristics. This study was directed towards

the fluid dynamic characteristics of both diffusers and ejectors particularly in combination, with special emphasis on radial flow devices. A supersonic radial-flow device, having a full 360° of flow, is being used to determine the basic characteristics of radial diffusion; in addition several linear flow devices and ejector systems were available for experimental research in flow induction. Theoretical analysis have been developed to support the programs.

## I. MIXING LAYER RESEARCH

The experimental studies on mixing layers were conducted in a continuous flow, direct current arc heated wind tunnel facility. Two overall nozzle configurations are employed as shown in Figure 1. In the baseline configuration (Figure 1a) both nozzles were supplied from the arc heated reservoir. In the two stream system, one nozzle was supplied by the arc heater reservoir while the other was separately supplied with an arbitrary unheated gas. The latter configuration allowed simulation of the large velocity and temperature differences which existed across adjacent nozzles in current chemical transfer lasers. Both contoured and wedge nozzle blocks were used in both configurations. In addition, the center nozzle element was designed for ease of replacement to allow a variety of mixing layer injection schemes to be investigated and the nozzle block holder permitted rapid alteration of the nozzle array configuration for different Mach numbers on internal injection methods. Operating with either air or molecular nitrogen, typical reservoir pressures and temperatures

were 1.0 atm and 2000°K, respectively. These conditions led to flow properties at the nozzle exit which simulate those in supersonic flow chemical lasers of current interest.

An electron beam provided the primary instrumentation system for analysis of the mixing region. In this technique, a narrow beam of electrons was projected across the flow in a direction perpendicular to the gas velocity. Profiles of gas properties were obtained by examining various points along the length of the electron beam and measurements were made at various stations downstream of the nozzle exit. The spatial resolution of the measurements in the flow direction was limited by the minimum diameter of the electron beam (2 mm). The resolution in the direction perpendicular to the mixing layer (parallel to the electron beam) was determined by the field of view of the optical system employed to collect the electron beam-induced radiation. Extensive optical optimization has been conducted to obtain a spatial resolution near .010 inches.

In conventional applications of an electron beam, only the steady state gas properties were measured. However, during the course of the present studies theoretical and experimental analyses have been conducted to allow isolation of the rotational temperatures turbulence, independent of fluctuations in other gas properties and electron beam operating parameters. This technique allowed direct measurement of the temperature turbulence at arbitrary locations within the flow field and yields data which could be used to judge the applicability of various turbulence and mixing models. In addition to the electron beam, conventional pitot

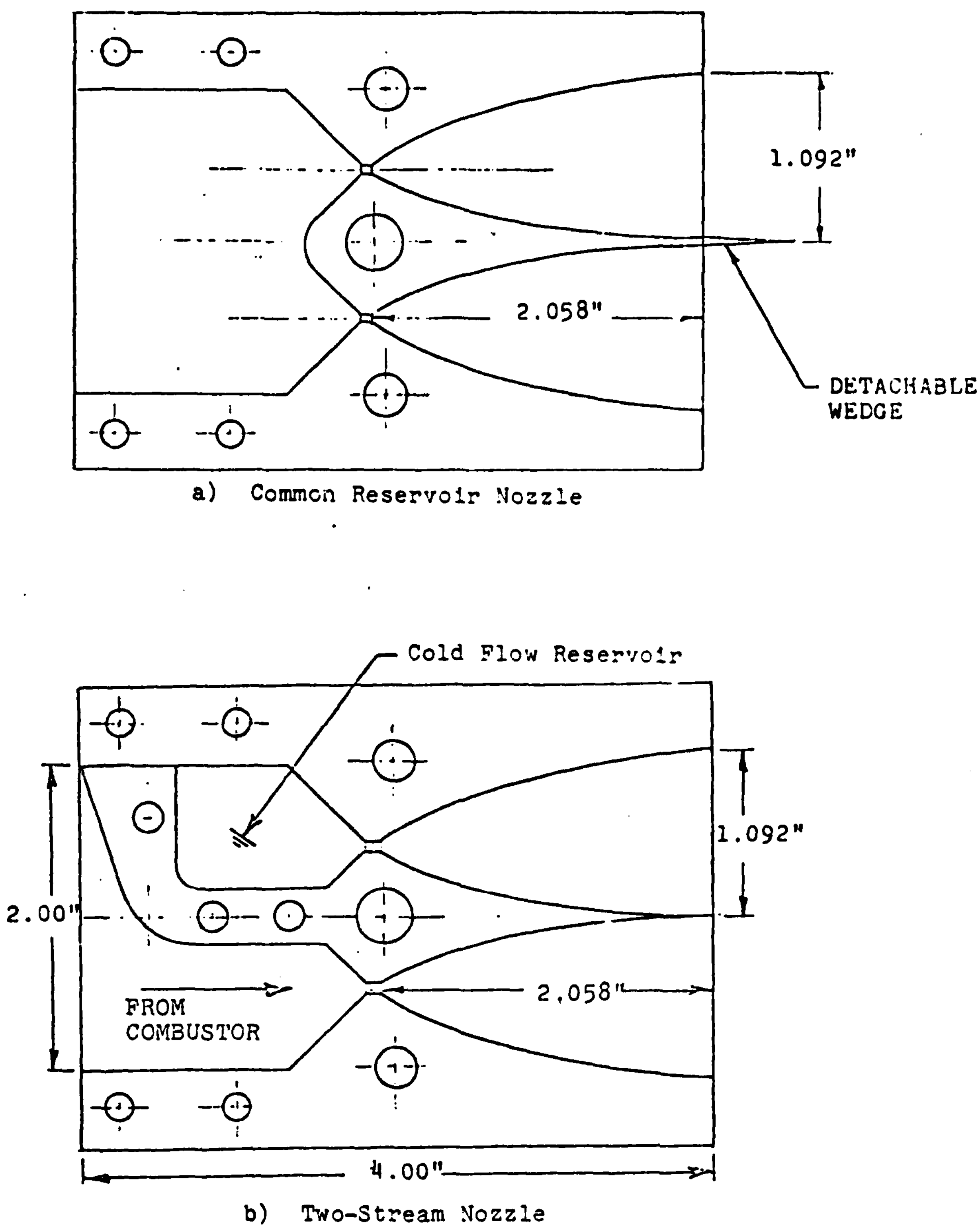



FIGURE 1. NOZZLE CONFIGURATIONS

pressure and mass flow probes were also used to examine the mixing region.

Particular emphasis has been placed on the continued development of a versatile numerical model for turbulent mixing of coplanar flows. The resulting computer program was capable of calculating laminar and turbulent two dimensional compressible boundary layer flows along a body and in wakes and free shear layers. Heat transfer to the nozzle wall was included in the analysis and appears to be particularly important for nozzle flows where the boundary layer was subjected to very high heat transfer rates in the region near the nozzle throat. Additionally, mass diffusion of a binary mixture was permitted in the shear layer subject to the assumption of unity Lewis number.

Closure of the system of equations was accomplished with one of a number of models. These included:

a. the Cebsci-Smith model
b. a Glushko single transport equation model
c. a two equation model
d. the Donaldson transport equation model

In a single transport equation model, the eddy viscosity was formed from the product of an algebraic length scale and a velocity obtained from a solution of the turbulent kinetic energy equation. The two equation model was developed from an eddy viscosity which was formed from a velocity and length scale that were both described by transport equations. This model used an energy equation and a dissipation rate equation expressed in terms of a pseudo-vorticity.

The computer program also allowed examination of the effects of boundary layer initial conditions on the calculated properties in the mixing region. For example, the influences of the high gradients in the nozzle throat region were included by specifying realistic edge conditions for the boundary layer solution. In addition, the influence of nozzle wall temperature on the predicted temperatures in the mixing layer appeared to be particularly important and was investigated with the computer program.

Momentum integral techniques are also being used to characterize the overall features of the mixing region. The advantage of this method that the many assumptions inherent in finite difference solutions are not required. Instead, an approximate unifying theory for laminar, transition and turbulent wake processes has been developed for application to both two-dimensional and axisymmetric geometries. Velocity and enthalpy profiles across the mixing region were obtained in terms of a velocity gradient parameter similar to the Pohlhausen pressure gradient parameter.

A large variety of numerical experiments have been conducted with the various options in the code to examine certain aspects of boundary layers and free shear layers. Comparisons with the present experimental results as well as with those from other investigators have also been conducted.

A major effort has been in extending the analyses to treat unsymmetrical free shear layers. This extension has been completed and typical results are included for illustration.

Since the static temperature fluctuation was the principal quantity measured in the experimental studies in progress,

significant effort has been devoted to obtaining accurate predictions of the temperature turbulence. Detailed analyses demonstrated that a reasonable relationship between the turbulence kinetic energy and and velocity fluctuations can be seen by $\overline{(u')^2} = AK$ where $\overline{(u')^2}$ denotes the mean of the square of the streamwise velocity fluctuations, K is the turbulent kinetic energy, and A is a constant to be determined. The experimental data of Kistler was used to determine A. These data are for supersonic turbulent boundary layers at Mach numbers of 1.72, 3.56 and 4.76 at Reynolds numbers between $2.88 \times 10^4$ and $4 \times 10^4$, based on momentum thickness.

In the three principal models used in this study, the turbulent kinetic energy was calculated explicitly in two--the Glushko model and the Jones and Launder model. The original Cebsci-Smith (CSM) model does not calculate the turbulent kinetic energy. This model has recently been extended to allow computation of the turbulent kinetic energy, leading to predictions of the temperature fluctuation.

Typical comparisons of the theoretical results with the boundary layer data of Kistler are shown in Figures 2-4.

For a Y/delta of more than approximately 0.6, the experimental data showed a more gradual drop off than do the predicted results but predictions agreed well with the data in the midregion of the profile. That the comparisons are good for the peaks is to be expected since the proportionality constant (A) was chosen on the basis of the peak value, but the agreement is good away from the peak and toward the edge.

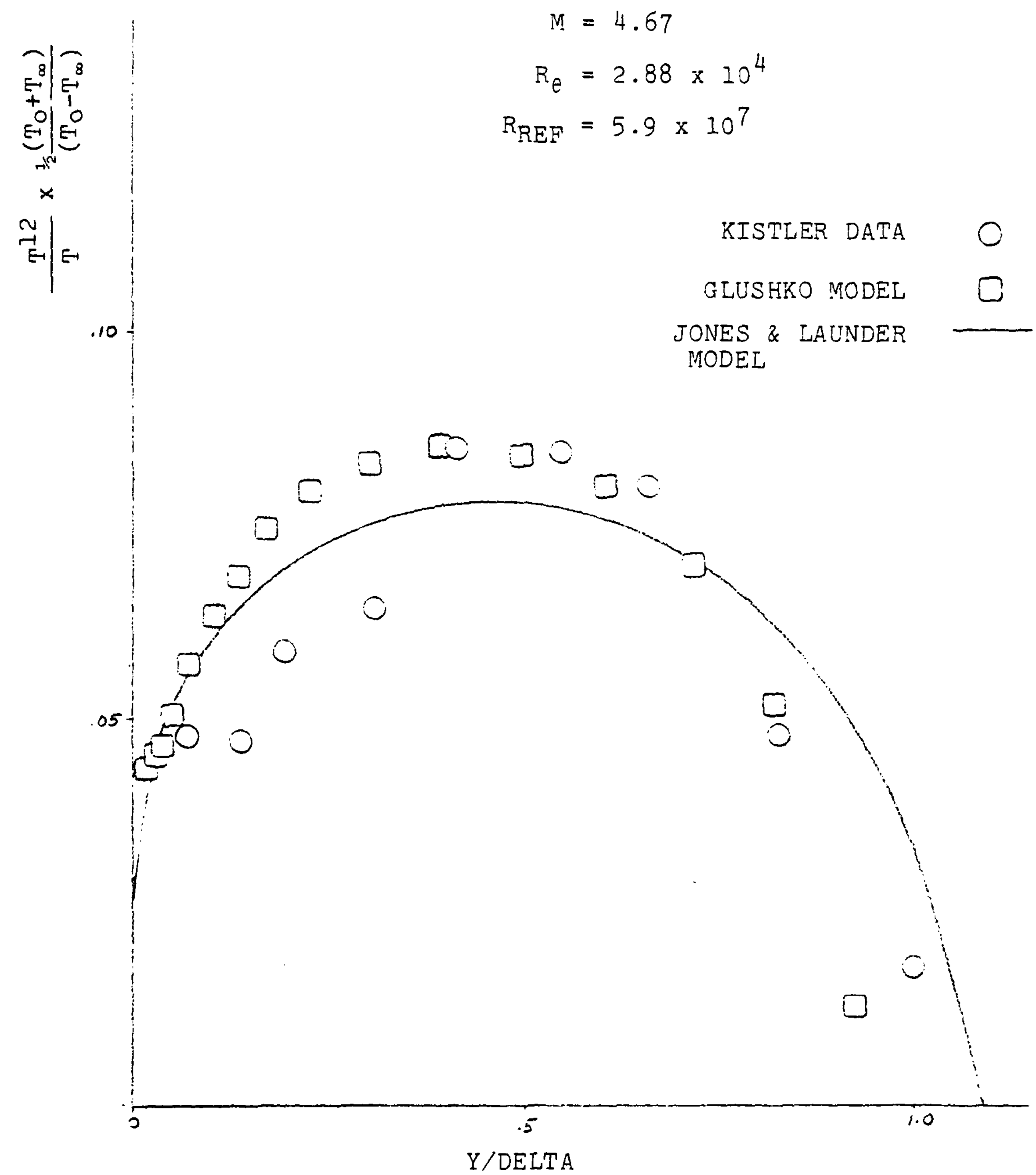



FIGURE 2.
COMPARISON OF AVAILABLE EXPERIMENTAL DATA WITH THEORY USING THE JONES & LAUNDER TURBULENCE MODEL.

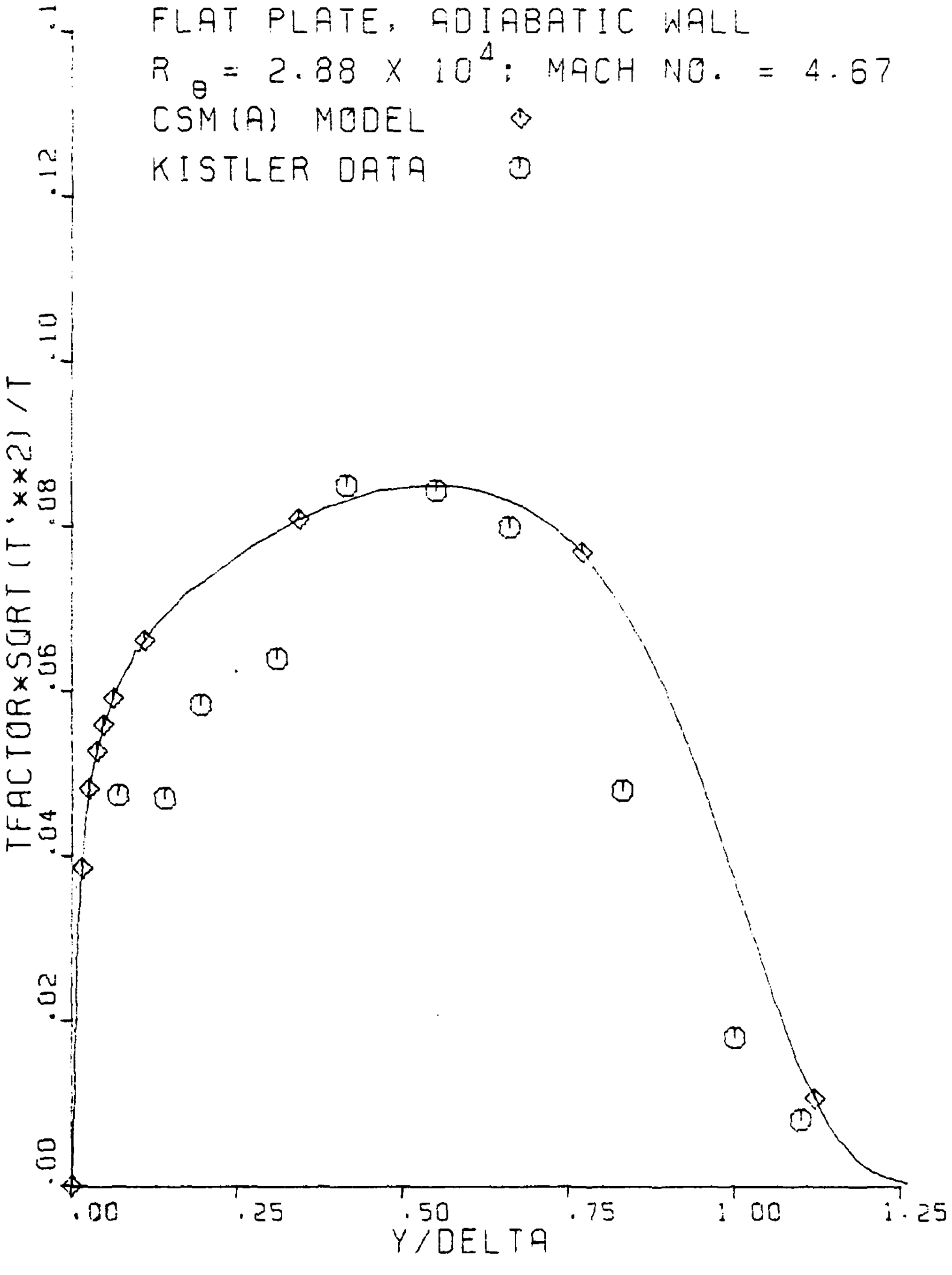



FIGURE 3.
COMPARISON OF AVAILABLE EXPERIMENTAL DATA WITH THEORY USING THE CSM MODEL

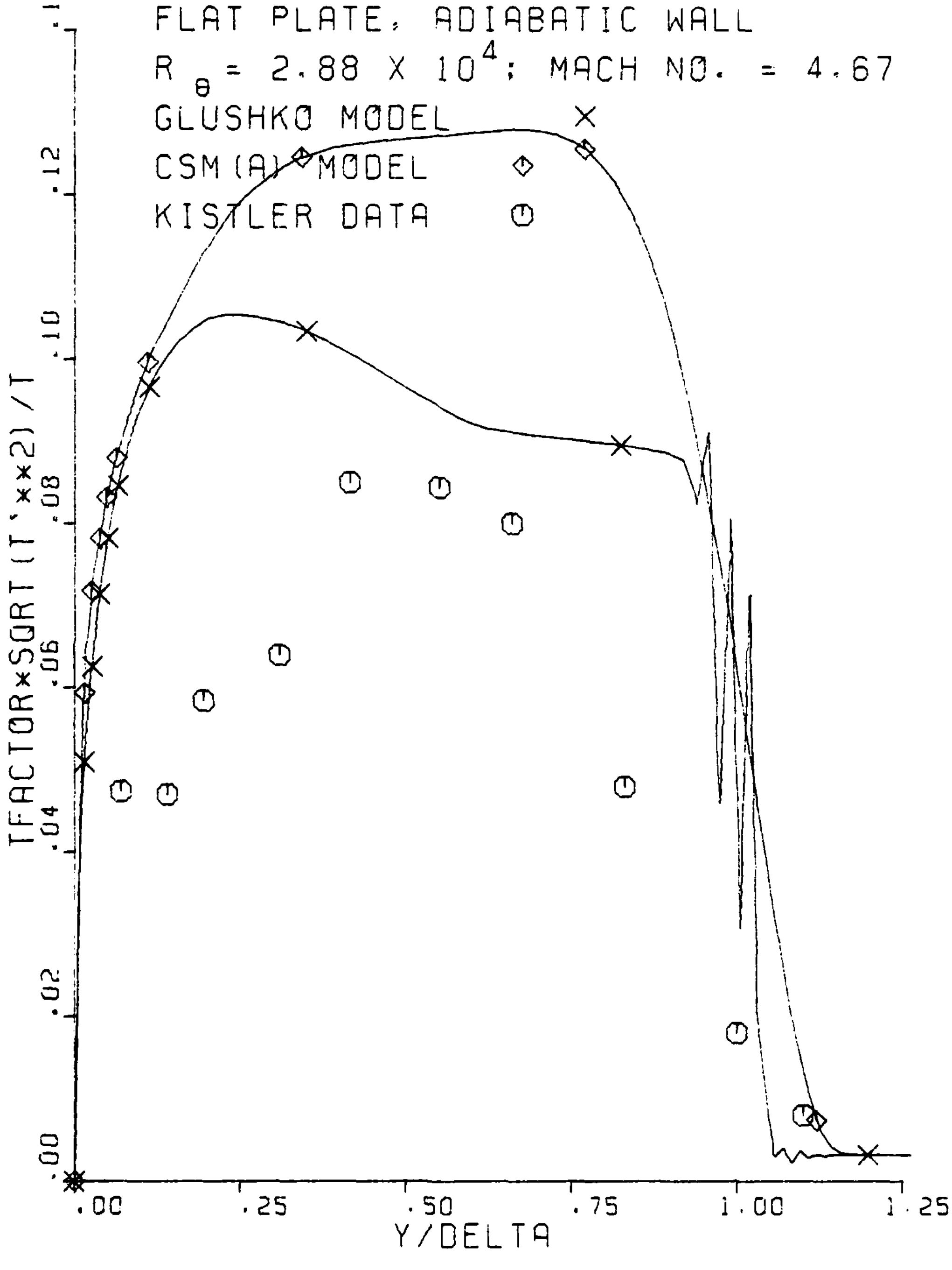



FIGURE 4.
COMPARISON OF AVAILABLE EXPERIMENTAL DATA WITH THEORY USING THE CSM AND THE GLUSHKO MODEL.

In the lower section of the boundary layer, the predictions always exceeded the experimental data. The greatest disparity was for the Mach number = 4.67 case for a Y/delta between about 0.1 and 0.3. However the experimental point closest to the wall was quite near the theoretical value.

Predictions using Donaldson's transport equation for the temperature fluctuations agreed very poorly with the experimental data. However, no adjustments of parameters was made on the transport equation. Such adjustments would improve the agreement.

For a symmetric mixing region, a number of experiments were conducted to assess the influence of wall temperature on the predicted temperature profiles. Typical results are shown in Figure 5. A wall enthalpy ratio of 0.143 gave the best fit to the experimental data, but the overall shape of the steady-state temperature profiles were not well-predicted by the theory. For the data of Figure 5, the theoretical profiles show a pronounced dip on the centerline while the experimental data show a maximum. The approach to a temperature ratio of 1.0 is also not well predicted. The theoretical curves show a comparatively rapid fall in a distance of approximately 0.12 in from centerline, while the experimental data show a much more gradual descent, falling off to a temperature ratio of 1.0 in approximately 0.3 inches.

While the detailed shapes of the temperature profiles are not well predicted by the theory, the maximum temperature ratios at the various stations show better agreement, as can be seen in Figure 6.

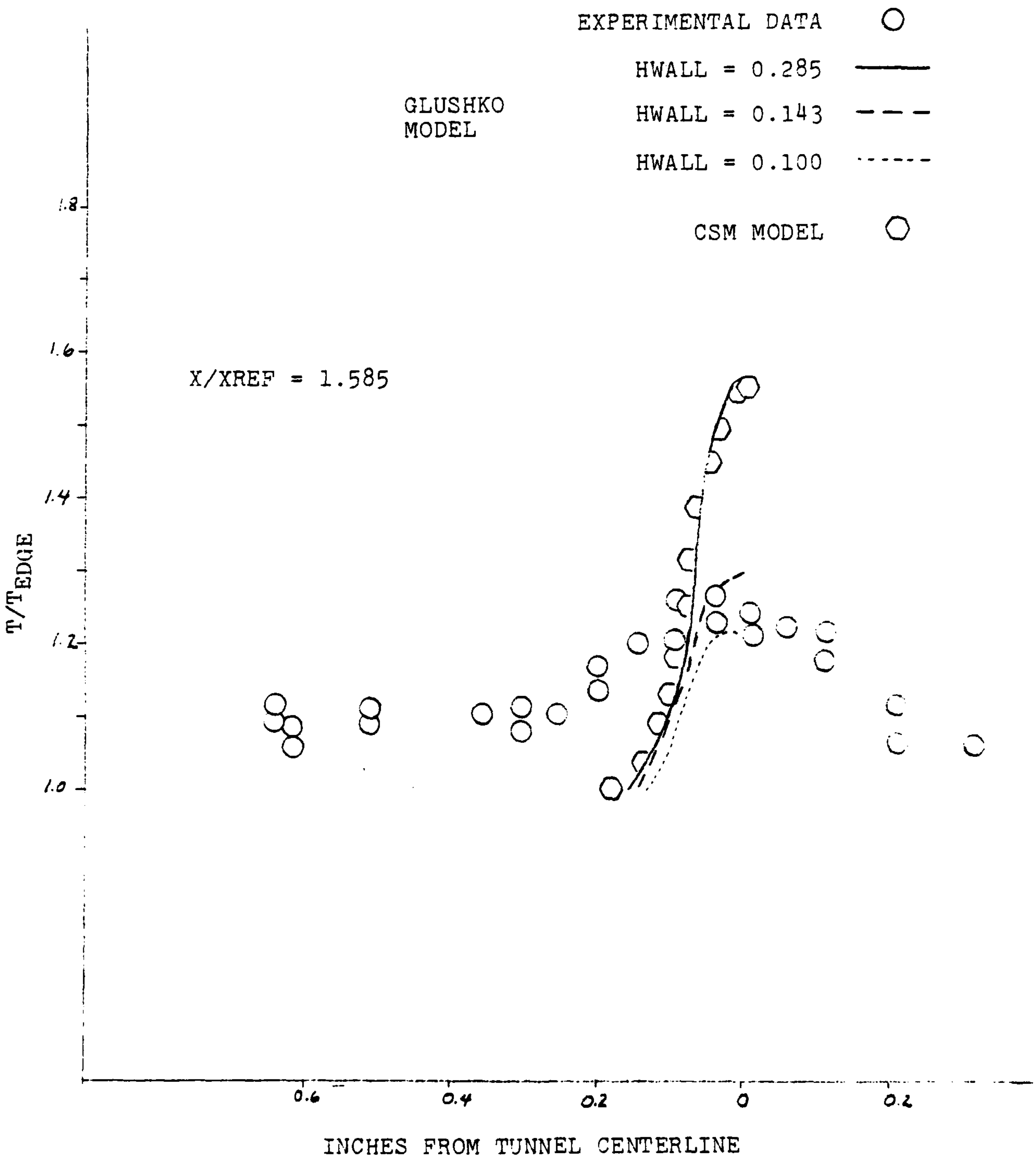



FIGURE 5.
COMPARISON OF OSU EXPERIMENTAL MEASUREMENTS WITH THEORY FOR $T/T_{EDGE}$ PROFILES.

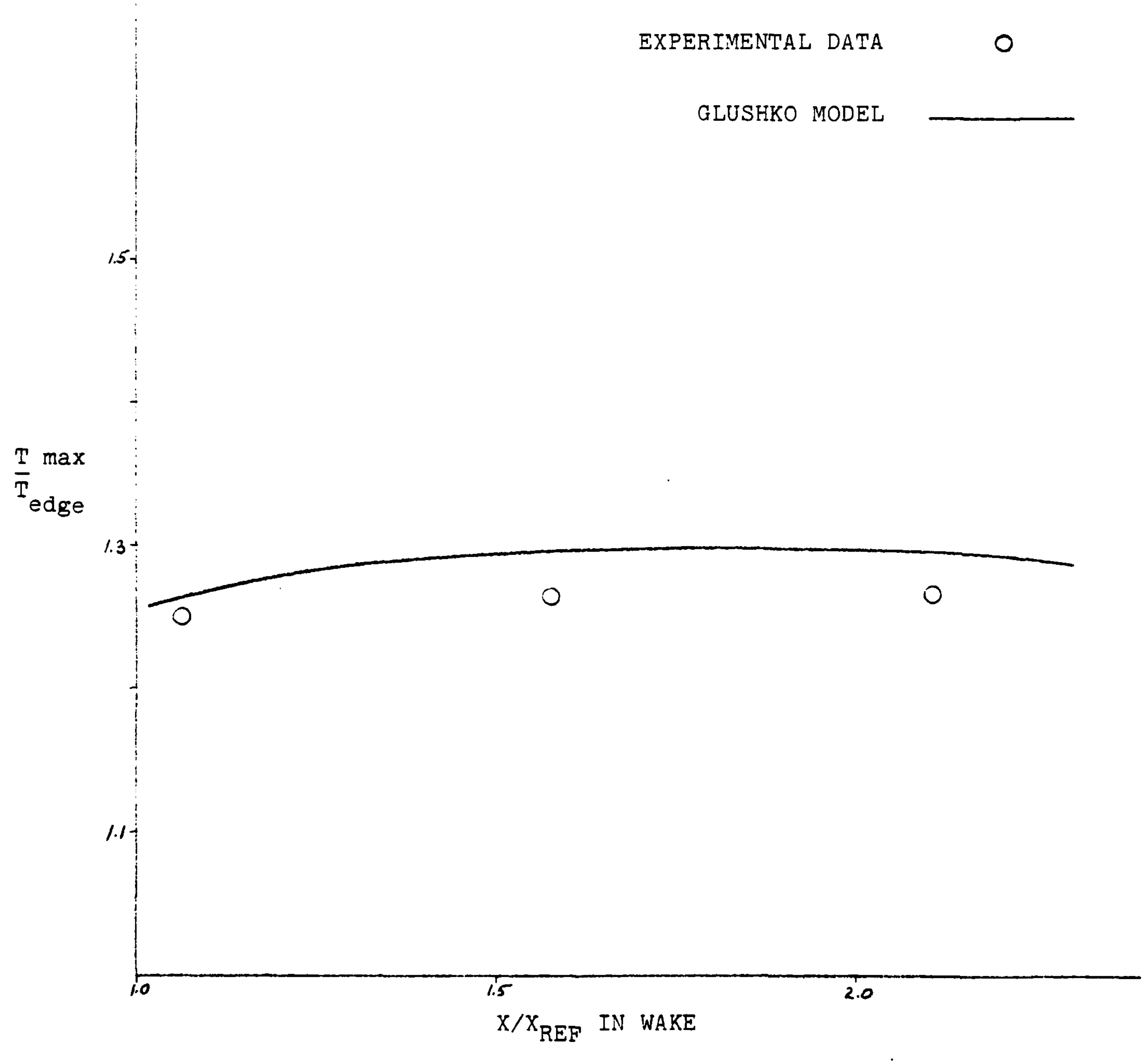



FIGURE 6.
COMPARISON OF OSU EXPERIMENTAL MEASUREMENTS
WITH THEORY FOR $T_{MAX}/T_{EDGE}$

The effects of upstream history on the mixing layer were studied by considering the wake to be that resulting from a flat plate. A typical effect on the mixing region with no pressure gradient formed by flows subjected to pressure gradients (flows within the nozzles) is shown in Figure 7. As can be seen, upstream history has a large effect upon subsequent mixing in the wake. In addition, it can be seen that for these profiles very near the nozzle exit turbulence had little effect upon the temperature ratio profiles.

Comparisons of the measured temperatures fluctuations with those using the Glushko model are given in Figure 8. The predicted profiles show a minimum on the centerline, while the experimental profile shows a maximum. In addition, the experimental profile is much broader than the predicted one, showing no pronounced peak. At the second station (x - 4.25 in.), both the experimental and predicted profiles taper off in approximately the same manner towards the freestream, and the maximum levels are close to being the same. The experimental data show a maximum on centerline while the predicted profiles show a minimum on centerline. Changing the wall enthalpy ratios by almost a factor of three did not improve the agreement in the shapes of the profiles, although the agreement in the maximum levels was somewhat improved.

To assess the predictive abilities of the various models for asymmetric wakes, the data of Spencer were chosen. The data were for velocity ratios of 0.2 and 0.6 at subsonic Mach numbers, where the ratio is defined as u2/ul, and $u_2$ and $u_1$ are the velocities of the slow and fast flows, respectively.

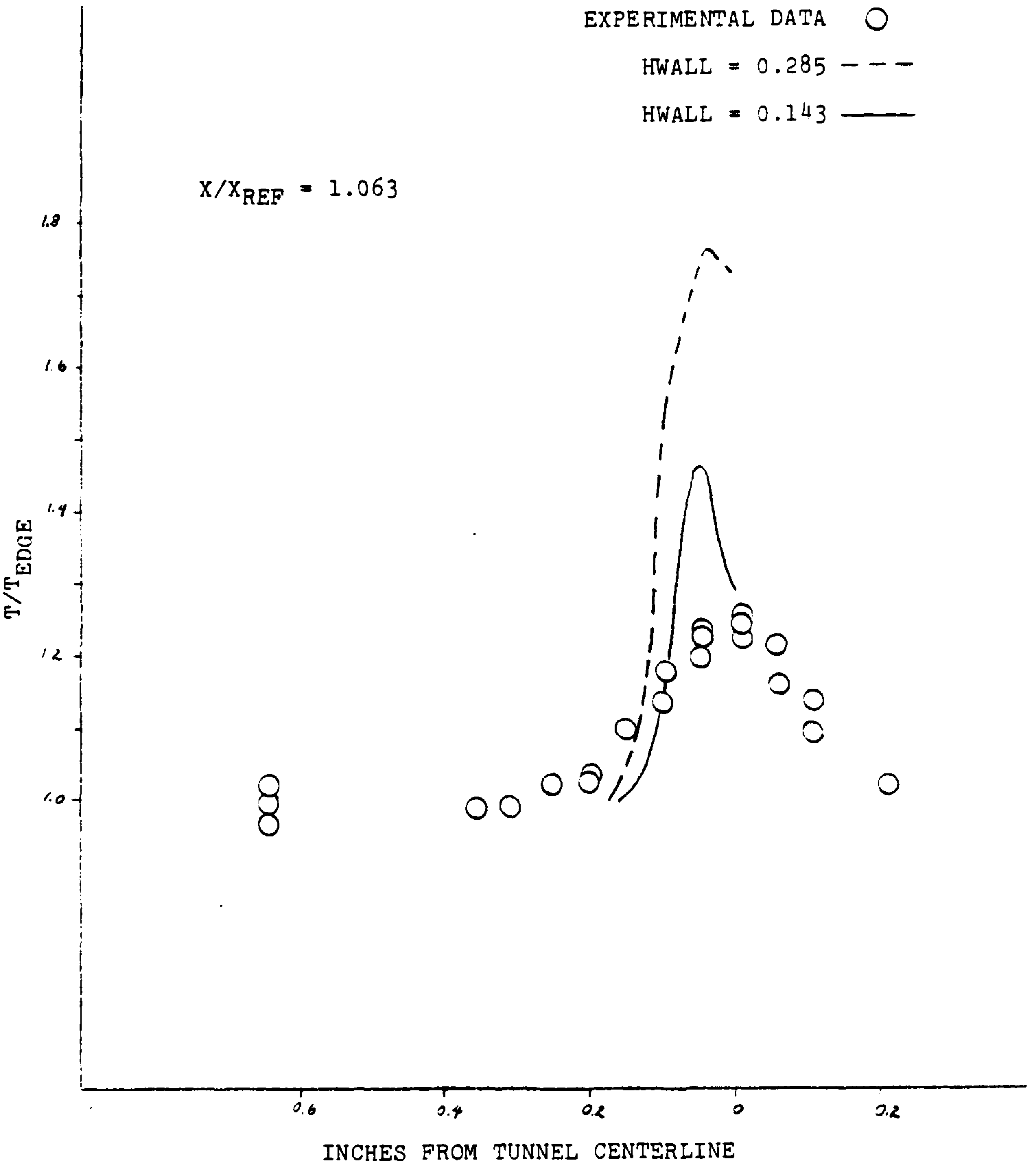



FIGURE 7. TEMPERATURE DISTRIBUTIONS, LAMINAR WAKE OF A FLAT PLATE.

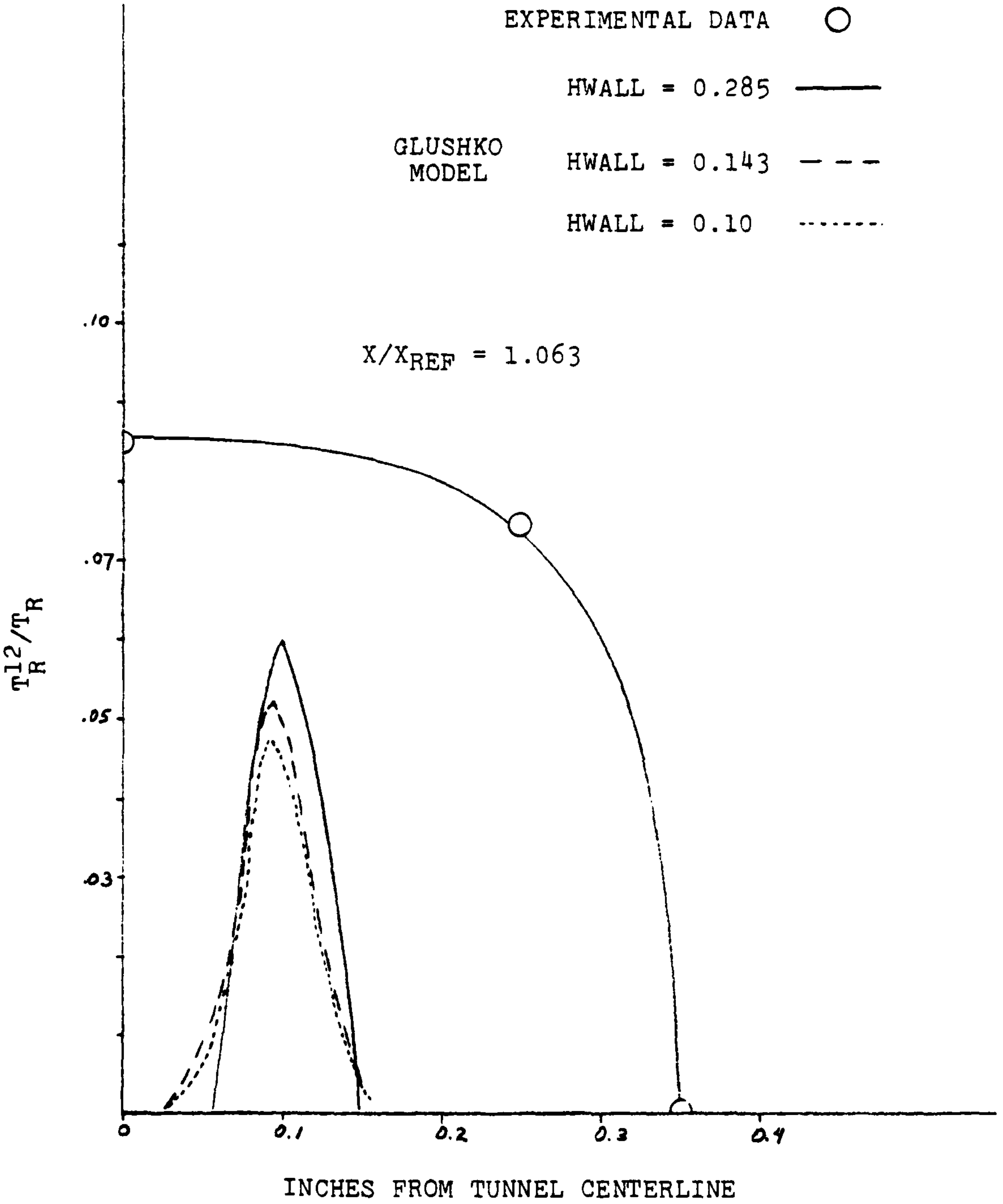



FIGURE 8.
COMPARISON OF THE THEORY USING THE GLUSHKO MODEL WITH MEASUREMENTS OF THE TEMPERATURE FLUCTUATIONS.

It is to be noted that only the Jones and Launder model does not require modification for asymmetric wakes since it was formulated for general flow situations. The CSM and Glushko models were originally formulated for symmetric wakes. These models were extended so that they could be used to predict the properties of asymmetric wakes.

A typical comparison of theory with experiment for the CSM model and a velocity ratio of 0.3 is shown in Figure 9. These calculations were performed with a fixed mixing length constant. Decreases in the constant by about 30% greatly improve the agreement of the theoretical and experimental results in the near wake, but cause worse agreement in the far wake. Alternatively, increases in the constant will reverse this trend. That is, the agreement can be improved in the far wake by increasing the mixing length constant, but the descrepancies in the near wake are increased. Hence, it appears that the mixing length "constant" must be considered to vary, at least in the flow direction.

The descrepancies between theoretical and experimental temperature results are under study. Experimental studies are currently in progress to define the temperature fluctuations with improved spatial resolution and signal-to-noise ratio. These measurements are now nearing completion.

## II. RADIAL FLOW RESEARCH

The characteristics of radial flow diffusers was studies in a continuous-flow device having a full 360° flow field from a perforated cylindrical nozzle delivering a Mach number of 2.85 in

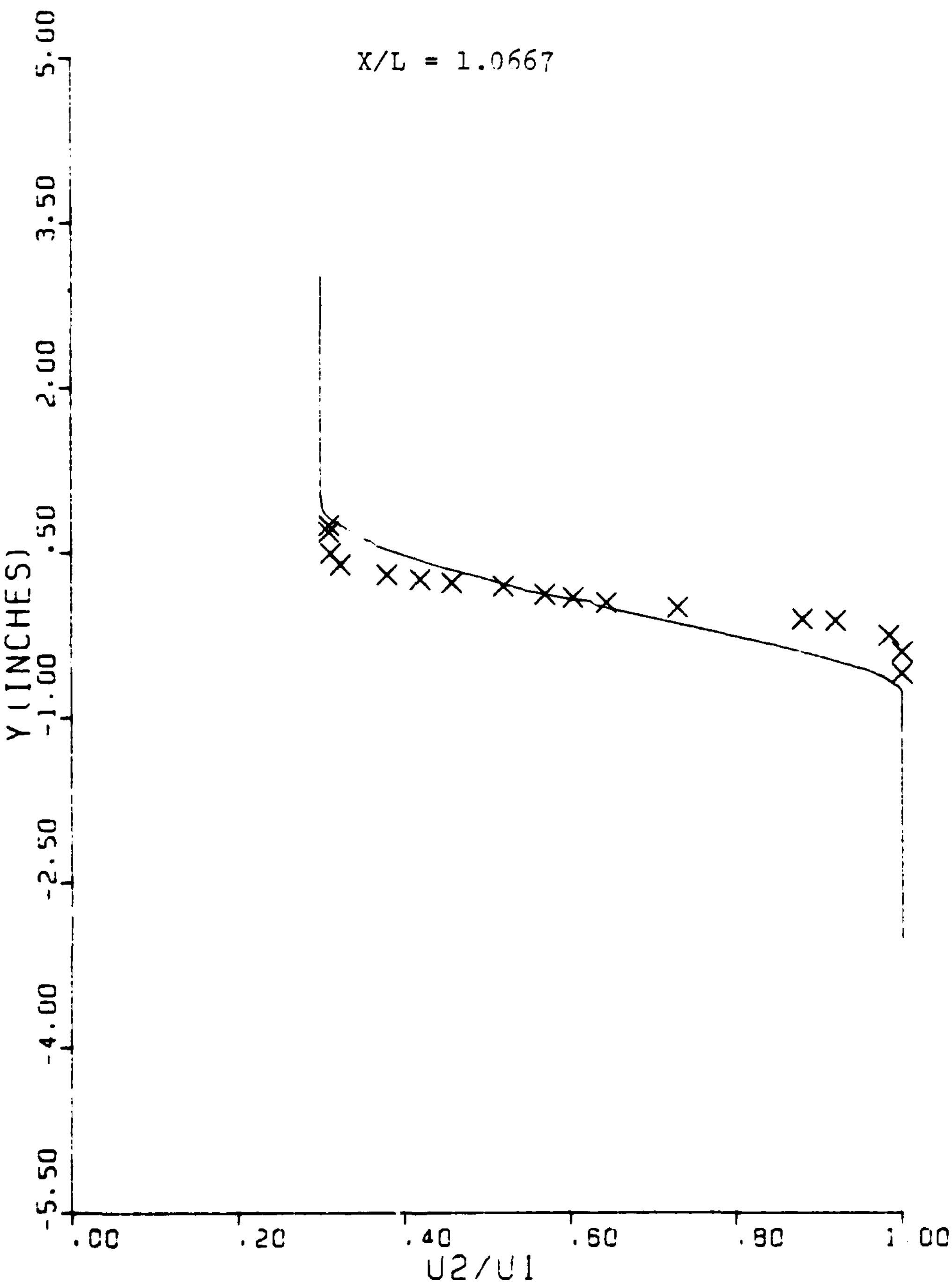



FIGURE 9.

COMPARISON OF EXPERIMENTAL DATA WITH THEORETICAL PREDICTIONS FOR TYPICAL VELOCITY PROFILE

the zone simulating a laser "cavity". The device was supplied with clean, dry air from the Laboratory's storage (1500 cubic feet at 2600 psia) and exhausts into the 15000 cfm pumping station. The system supplied a sufficient pressure ratio to operate the device with minimal diffusion, i.e. with plane walls throughout and could also be controlled in order to simulate transient operation. Pressure variation permitted the complete simulation of the Reynolds number range of lasers. Photographs of the device which was used in the study are shown in Figure 10: a typical pair of diffuser discs, their installation on the walls, and the complete assembly.

Early diffuser research was initiated with a 6 in. by 6 in. supersonic linear channel having a contoured slat nozzle delivering a Mach number of 2.5 and into which was mounted a series of slat-diffuser vanes. Although no important differences were found in the configurations since all delivered recoveries of about 0.82 of normal shock, it was concluded that the use of multiple vanes was a feasible means of reducing the length of the diffusion channel. However, analytical work at that time suggested that the results from the linear device would have only limited application to radial flows over the desired range due to (a) the gradients existing in radial devices and (b) the level of Reynolds number. For these reasons the radial-flow device was designed and fabricated. The design was bounded by the necessity to obtain a full, 360° flow field so that boundary interactions could be properly evaluated, but within this restriction it was found possible to operate a device of sufficient

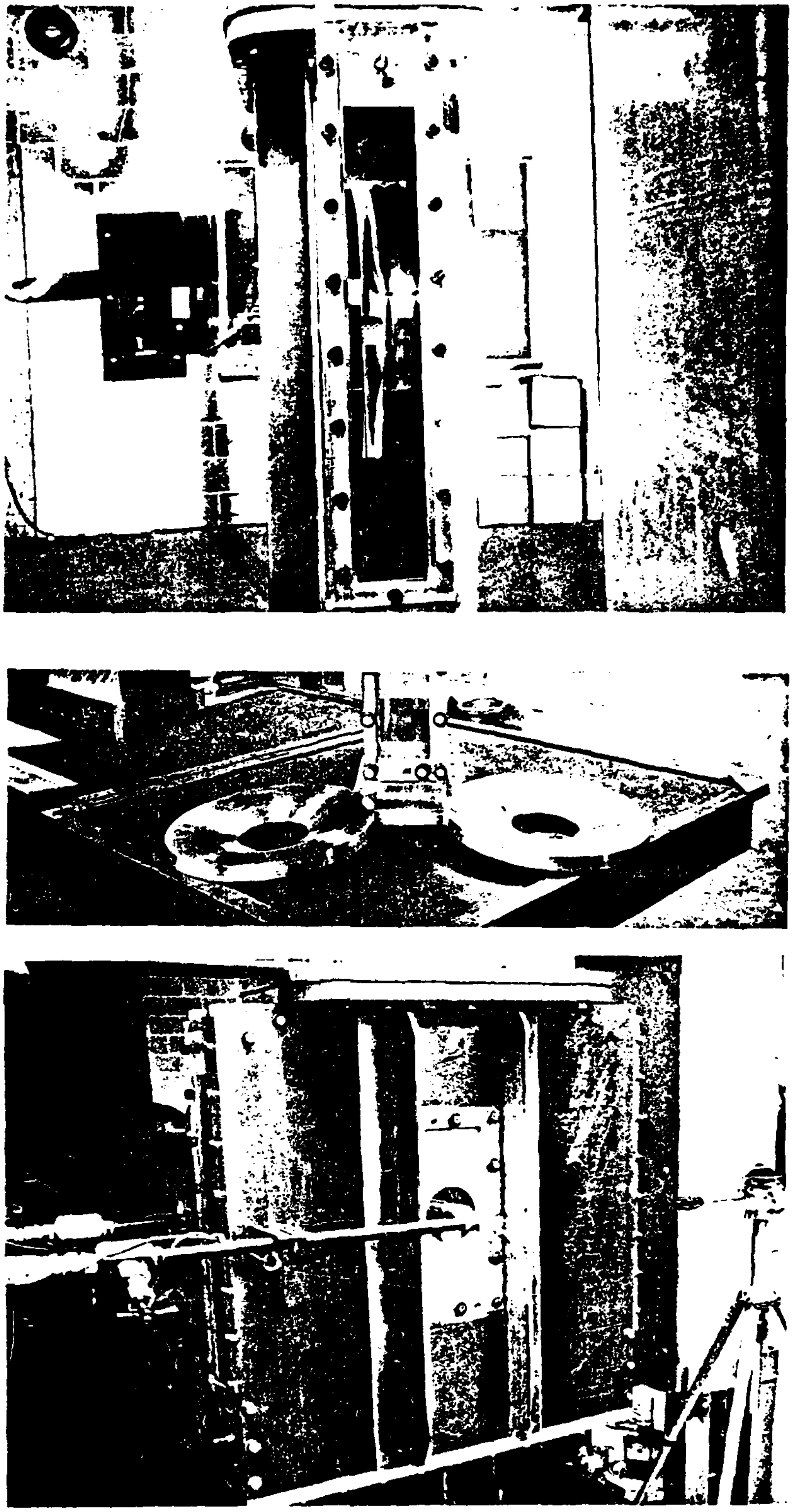


FIGURE 10. A TYPICAL SET OF RADIAL DIFFUSER DISCS, DISCS MOUNTED ON SIDEWALLS, AND FULL ASSEMBLED RADIAL FLOW DEVICE.

size to be useful. Initial tests were conducted to explore the operating boundaries and during this phase, screen-tubes were added to the nozzle interior to remove non-uniformities in the supply flow.

A wedge was installed to simulate the presence of a radial plane boundary as it would exist in a partial-radial-flow device, to determine if the use of such a flow device was feasible since a larger size could then be tested in any available situation. Schlieren photos showed that, in the range of Reynolds numbers desired, the boundary interacted severly with radial field, so that the "non-radial" zone extended to at least 45° from the boundary. Thus, for example, in a 90°-segment "simulator" all of the flow would be under the influence of the boundary walls and there would be no part of the field simulating true radial flow. Hence realistic research can only be conducted in a device having a clear 360° flow field.

Figure 11 shows Schlieren views of the clear flow field, before installation of any diffuser sections, along and normal to the nozzle axis. With the diffuser discs installed only the center section of the flow field is visible, as shown in Figure 12 for a partially-started flow and a fully-started flow.

Theoretical analysis techniques were developed to provide direction in the design of the diffuser walls and an understanding of the flow mechanisms, in conjunctions with measurements of surface pressures and Schlieren photos. A one-dimensional analysis was used to provide integral information and the early diffuser shapes. A two-dimensional method was developed,

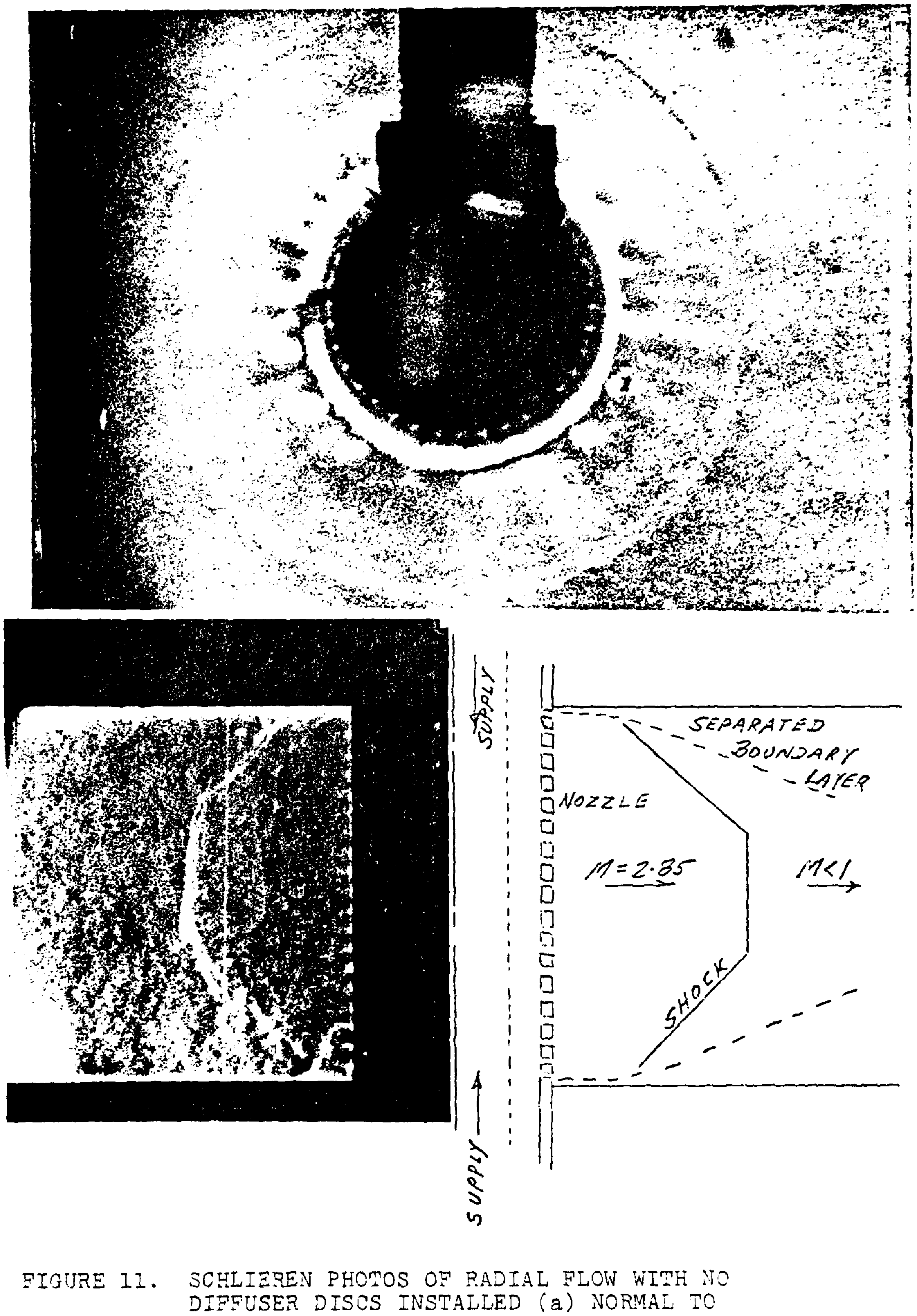



FIGURE 11. SCHLIEREN PHOTOS OF RADIAL FLOW WITH NO DIFFUSER DISCS INSTALLED (a) NORMAL TO AND (b) PARALLEL TO NOZZLE AXIS.

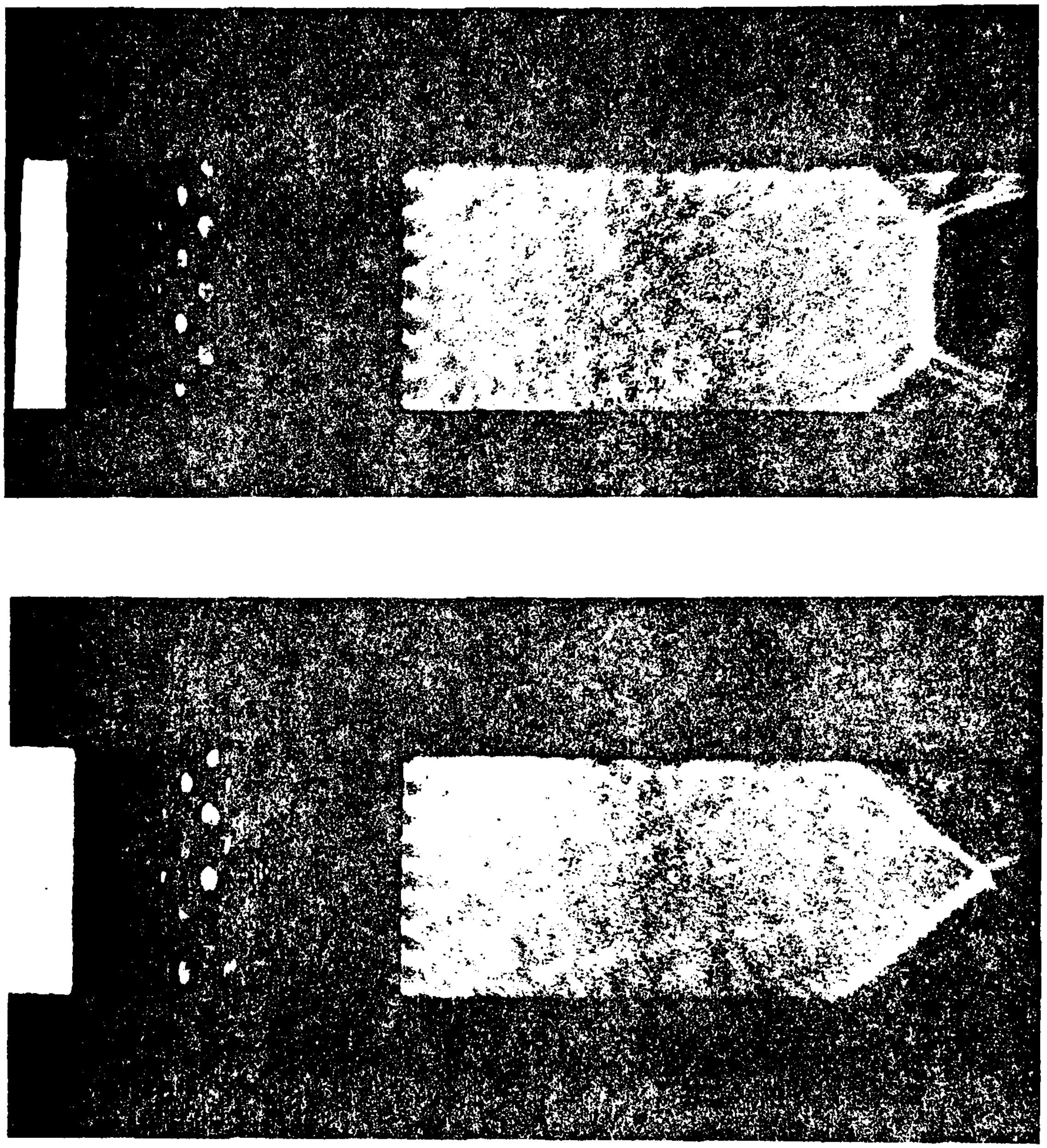
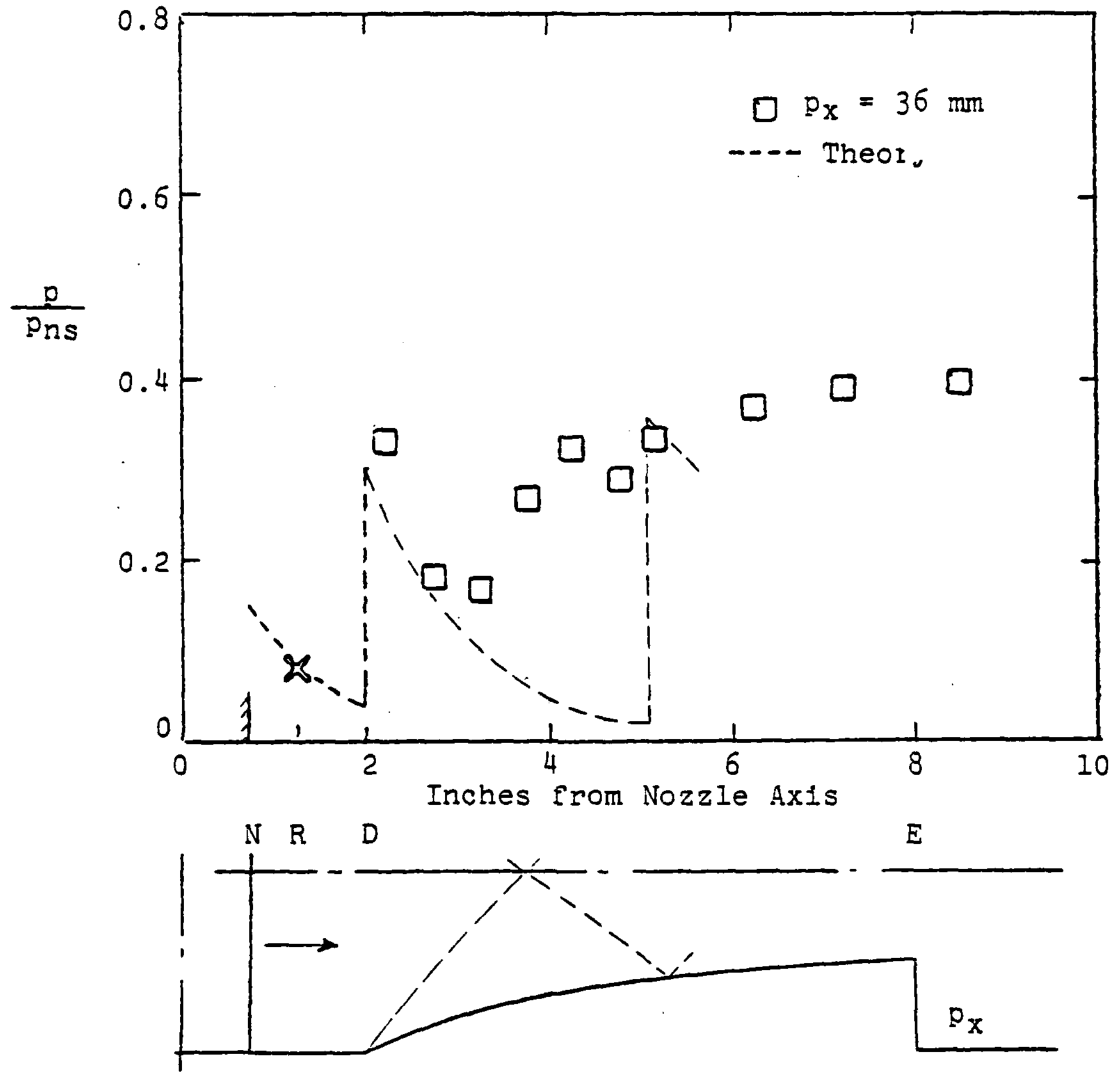


FIGURE 12. SCHLIEREN PHOTOS OF RADIAL FLOW (PARTIALLY OBSCURED BY DIFFUSER WALLS), PARTIALLY-STARTED AND FULLY DEVELOPED.

incorporating radial characteristics and oblique shock interactions. A typical prediction of the surface static pressure is compared with the measurements in Figure 13; the descrepancies are due to an extensive separation of the boundary layer. This theoretical technique has been extended and used to study the influence of surface shape geometry on the shock wave and the possible recovery levels with a view to both relieving the separation and to optimizing the recovery. However, the viscous effects are so extensive that accurate predictions will be possible only with the inclusion of a theoretical treatment of the boundary layer and the associated separated zone.

## SUMMARY AND CONCLUSION

Theoretical and experimental studies have been conducted on mixing layers and on radial flows. Measurements of both mean and fluctuating properties of the interface between two streams generated from an arc-heated wind tunnel were made by means of an electron beam. Theoretical models were developed to compare with and predict these measurements. Radial supersonic flows were examined in experimental devices and by theoretical analyses to determine the nature of such flows during diffusion and to predict the associated wave systems and boundary layer phenomena.




N Cylindrical Nozzle

R Reference Point

D Diffuser Entrance

E Diffuser Exhaust

FIGURE 13. TYPICAL STATIC PRESSURE DISTRIBUTIONS ALONG ONE SURFACE OF A DISC DIFFUSER COMPARED WITH THEORY (INVISCID) BY SHOCK + RADIAL CHARACTERISTICS.